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A CASE STUDY TOWARDS ASSESSING THE IMPACT OF MIXED REALITY-BASED INSPECTION AND RESOLUTION OF MEP ISSUES DURING CONSTRUCTION

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SUMMARY: *Despite advances in 3D clash detection during preconstruction, mechanical, electrical, and plumbing (MEP) installations are still prone to the detection of unforeseen clashes during construction. These issues must be resolved as quickly as possible to prevent significant schedule delays. Through interviews and field observations, this case study investigates the impact of mixed reality (MR) on the inspection and resolution of field-detected MEP issues from product, organization, and process (POP) perspectives. For the product impact, preliminary findings from the field interviews show that MR-based inspection would increase the quality of MEP installation by identifying errors easily and resolving them faster. For the organizational impact, we modeled and compared the current (as-is) and MR-integrated (to-be) MEP field issue resolution workflows using Business Process Model and Notation (BPMN) and determined that MR-based inspections can decrease the coordination overhead between MEP engineers and superintendents by up to 75%. This translates into at least a 50% faster resolution of an MEP issue for the process impact. The paper contributes to the practice of MR-based field inspection by providing a method to quantify potential time savings by integrating MR into the MEP field issue resolution workflow and field interview questions for MEP engineers and superintendents to further examine the use of MR during inspection activities in construction projects. Our observations of MEP superintendents and engineers during field inspection showed that not all building information visualized in MR is useful for their inspection tasks. We developed a classification for building information usefulness to help construction project managers who are deploying MR determine useful information for the task at hand that needs to be integrated into the 3D MR model for MR-based inspections.*

***KEYWORDS**: Mixed Reality (MR), construction, MEP, inspection, information usefulness, Business Process Model and Notation (BPMN), Building Information Modeling (BIM)*

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1. INTRODUCTION

Through Building Information Modeling (BIM) coordination, construction project teams aim to identify potential conflicts between building components and resolve them before construction starts. Yet, previously overlooked conflicts during the BIM coordination phase often result in field issues during construction (Alsuhaibani et al., 2022). Timely resolution of these issues is critical to avoid schedule overruns. This requires effective collaboration between the project engineers in the office and superintendents in the field. Traditionally, superintendents have less expertise in using BIM software, which requires project engineers to assist them in navigating 3D models for issue inspection. Hence, project engineers and superintendents spend additional coordination effort, the resolution of field issues is delayed, and the quality of construction is negatively impacted. Mixed Reality (MR) technology can lower the expertise barrier for BIM by overlaying the 3D model onto the field accurately (Kopsida and Brilakis, 2020) and help construction project teams save time on field inspections compared to using the traditional methods (Choi and Park, 2021).

In contrast to the fast pace of information technology development, the construction industry remains one of the least digitized industries (Agarwal et al., 2016). One of the barriers to its digitization is the lack of studies that quantify the impacts of new technologies on construction projects (Noghabaei et al., 2020). For example, construction managers need to understand the impact of MR use on their construction project to decide whether and how to deploy MR. However, prior MR studies in the construction industry were mostly conducted in experimental settings. Koskela and Kazi (2003) indicate that information technology affects construction projects indirectly by transforming workflows. We consider MR as an emerging information technology and extend state-of-the-art MR research in the construction industry by modeling and comparing as-is (non-MR) and to-be (MR) field inspection workflows. We accomplish this goal: (1) by demonstrating the product, organization, and process (POP) impact through interviews, field tests, and workflow comparison and (2) by classifying the building information embedded in MR in terms of its usefulness for field inspection tasks. Therefore, this paper provides two contributions:

1) A method to assess the impact of MR-based field inspection using the product, organization, and process (POP) framework.
2) A usefulness classification of the building information embedded in MR-based BIM software that enables a construction project team to achieve expected product, organization, and process impact.

To demonstrate the POP-based assessment of MR use and building information usefulness classification, we conducted an MEP-focused case study on a construction project. The paper presents preliminary findings and recommendations for construction project teams who are applying MR during a construction field inspection.

2. BACKGROUND

Augmented reality (AR) technology superimposes digital information such as a 3D building information model over a physical environment. By increasing the interaction with the 3D virtual objects as if they are part of the physical environment, MR enables field workers to engage in construction activities hand-free. Although the research on MR in architecture, engineering, construction, and operation (AECO) dates to 2005 (Dunston and Wang, 2005), the release of Microsoft HoloLens as a commercial mixed-reality headset in 2017 was a milestone for the broader use of MR in the AECO industry (Cheng et al., 2020).

Our MR study builds on the previous research on AR/MR. We present related work focusing on (1) AR/MR applications in AECO, (2) research comparing field inspection with AR/MR to conventional inspection, and (3) research on building information requirements for AR/MR-based field inspections.

2.1. AR/MR applications in AECO

To understand the extent of AR/MR applications in AECO, we studied previous research that conducted systematic literature reviews in this area. Cheng et al. (2020) reviewed 87 papers published up to 2018 and categorized them under four categories: architectural and engineering design; construction; operation; and applications in the combination of these three categories. Among the selected papers, 49% of them are focusing on construction applications. Khan et al. (2021) reviewed and summarized the prominent applications of AR/MR in design, construction, and operation. Similar to the review by Cheng et al. (2020), the selected AR/MR papers on the construction phase applications (42 papers) were 76% of all phases (55 papers) combined. These reviews indicate that prominent applications of AR/MR in construction are construction management, site monitoring and inspection of site defects, inspection, information retrieval, and sharing, facilitating construction tasks, and construction worker and equipment operator training.

Wu et al. (2021) followed a different approach and categorized the application based on four purposes: task guidance and information retrieval; design review and refinement; process planning and control; and upskilling of the AEC workforce. The first category corresponds to the construction applications, which contained the highest number of papers compared to other categories. Lastly, Assila et al. (2022) categorized AR/MR applications in project phases. Their findings show that AR/MR applications are more developed in the construction and operation stages, which can be attributed to the benefits of AR/MR for real-time construction review (Assila et al., 2022); for example, identifying deviations from the 3D model.

Although previous literature reviews on the applications of AR/MR in AECO demonstrated a wide range of use cases in the life cycle of building projects, the extent of AR/MR studies in the construction phase compared to other phases show that AR/MR-based construction applications are relatively more developed, making them ready for adoption in the construction industry. However, there is a need for industry-focused case studies to guide construction managers decide whether and how to use these technologies on their construction projects. This study aims to address this need by demonstrating the impact of MR-based field inspections on a construction project.

2.2. POP-based impact of AR/MR use for construction inspection

Our research builds on the prior studies that assessed the impact of AR/MR use on construction field inspections. Using Science Direct and Scopus, we identified 791 papers on AR/MR use in the AECO industry that were published between 2005 and 2023. Among them, only 95 papers contained the word, “inspect” in their abstract or title. We reviewed 16 papers that evaluate the impact of AR/MR on field inspection to the conventional 2D-based inspection. We analyzed these papers based on the categories of the POP Framework developed at the Center for Integrated Facility Engineering at Stanford University (Kunz and Fischer, 2012). In this framework, the product represents the physical building or its digital representation as a 3D model, the organization represents the project team and any stakeholder who plays a role in designing, building, and operating the product, and the process represents the activities and work processes of the organization for designing, building, or operating the product (Fischer et al., 2017). Table 1 shows related research studies using the product, organization, and process-related metrics applied to assess the AR/MR-based inspection task.

TABLE 1: POP-based categorization of AR/MR-use impact on construction inspection.

Reference	Product	Organization	Process
Hammad et al., 2005	-	Workload	Automated information retrieval
Kamat and El-Tawil, 2007	Accuracy of identified damage	-	Inspection time saving
Shin and Dunston, 2009	-	Productivity and workload	Inspection time saving
Park et al., 2013	Reduction in defects	-	-
Kwon et al., 2014	Reduction in defects	Reduced field visit and rework	Inspection time saving
Moon et al., 2015	-	Operational effectiveness	Inspection time saving
Zhou et al., 2017	-	Workload	Inspection time saving
Riexinger et al., 2018	Reduction in defects	Productivity	-
Feng and Chen, 2019	-	Workload	Inspection time saving
Kwiatek et al., 2019	Reduction in defects	Productivity	Inspection time saving
Abbas et al., 2020	Accuracy of identified defects	Workload	Inspection time saving
Chen et al., 2020	-	-	Inspection time saving
Harikrishnan et al., 2021	-	Reduced field visits	Inspection time saving
Kim and Olsen, 2021	Accuracy of identified defects	Productivity	-
Nguyen et al., 2022	-	-	Real-time defect mapping
May et al., 2022	Accuracy of identified defects	Workload	Inspection time saving

2.2.1. Product

Previous studies evaluated the impact of AR/MR on product-related performance in two ways. First, when AR/MR is used proactively for defect management, it can reduce the number of defects that require rework in the field (Kwiatek et al., 2019; Kwon et al., 2014; Park et al., 2013; Riexinger et al., 2018), which increases installation quality. Second, when AR/MR is used during field inspection to retrospectively identify defects or deviations from design, it can help field inspectors accurately identify these defects (Abbas et al., 2020; Kamat and El-Tawil, 2007; Kim and Olsen, 2021; May et al., 2022). Timely identification of these defects is important for their timely resolution. This also prevents other conflicts that may arise from previously unresolved or overlooked defects.

2.2.2. Organization

In the context of field inspections, the organization consists of field inspectors, engineers, defect managers, installers, and other construction project members who are directly affected by the field-detected issue. Previous studies suggest that AR/MR-based inspection can positively impact these project members by (1) increasing productivity (Kim and Olsen, 2021; Kwiatek et al., 2019; Riexinger et al., 2018; Shin and Dunston, 2009), (2) decreasing workload (Abbas et al., 2020; Feng and Chen, 2019; Hammad et al., 2005; May et al., 2022; Zhou et al., 2017), (3) reducing the need for field visits to conduct inspections (Harikrishnan et al., 2021; Kwon et al., 2014), and (4) increasing the operational effectiveness (Moon et al., 2015).

2.2.3. Process

The efficiency of inspecting and resolving field-detected issues is important for eliminating schedule overruns during construction. Several studies that developed AR/MR-based field inspection methods suggest that AR/MR can help inspectors save time by reducing the inspection task completion time (Abbas et al., 2020; Kamat and El-Tawil, 2007; Kwiatek et al., 2019; Kwon et al., 2014; May et al., 2022; Shin and Dunston, 2009; Zhou et al., 2017). In addition, the efficiency of the field inspection process can be improved by monitoring damage development in real-time and creating a deterioration model (Nguyen et al., 2022), and automatically retrieving task-related information (Hammad et al., 2005).

Among 16 studies, 4 of them (Abbas et al., 2020; Kwiatek et al., 2019; Kwon et al., 2014; May et al., 2022) conducted a comprehensive analysis by considering the impact of AR/MR on POP. However, these studies were mostly performed in experimental settings lacking real construction project context. Our study extends these studies by conducting a case study to understand the impact of MR-based inspections in a construction project.

2.3. Building information requirements for AR/MR-based inspection

Construction field inspection aims to assess the quality, and progress, and identify issues by comparing completed work to construction documents. The information needs of field inspectors change based on the inspection task they perform (Sunkpho et al., 2005) at different stages of a construction project. AR/MR-based applications need to display relevant information regarding location, and specification requirements (Abbas et al., 2020) to address the interaction needs of field inspectors and increase their performance. Previously, Kamat and El-Tawil (2007) developed an AR-based interaction prototype to retrieve related information that is task and location-specific in the construction field. Later, Park et al. (2013) built an AR-based retrieval of work-specific building information such as material, and schedule to inspect field defects. More recently, Feng and Chen (2019) demonstrated the effectiveness of MR-based field inspection by retrieving the required information such as 3D geometry, material, spacing, etc. during a field inspection. Nguyen et al. (2022) developed an application for MR-based bridge inspection by integrating 3D geometry and related building information to assist the off-site inspection process. Our research brings a new perspective by analyzing the MEP-focused building information needs and testing the MR technology with target users in the field.

3. METHODOLOGY

This study presents a case study towards defining metrics and methods for holistically assessing the impact of MR use on the product, organization, and process of construction projects. While previous research on MR in the construction industry has demonstrated the benefits of MR in experimental studies on task-level performance, we aim to provide a new perspective by offering insights on operational-level performance in a real construction project setting. To achieve this, we applied case study research methodology using qualitative and quantitative constructs (Eisenhardt, 1989). By conducting a case study on a construction project, we investigated the impact of MR-based inspections on the product, organization, and process of field-detected MEP issue resolution.

3.1.Case study: Life science project

The construction project selected for the case study was a 454,000-square-foot life science project built in South San Francisco. The construction project included complex overhead MEP and lab equipment that require coordination at Level of Detail (LOD) 400. For the seamless execution of the weekly schedule, the project engineers must resolve MEP field issues identified by superintendents during installations as quickly as possible by comparing the 3D model to the field construction. To determine the business need for conducting a pilot MR study we interviewed the virtual design and construction (VDC) engineer whose role was to coordinate the issue resolution process. We learned the inefficiencies in the current workflow of field issue resolution between superintendents and project engineers. In the current workflow, when superintendents identify an MEP field issue, they ask project engineers for a walkthrough of the 3D model because the BIM software requires a laptop and BIM expertise. This need for assistance increases the coordination overhead between superintendents and project engineers, and ultimately, delays the resolution of field-detected issues. Based on the identified MR use objective in the case study, we defined the following research questions:

RQ1: How does MR-based BIM facilitate the inspection of MEP installation issues in the construction field? (Product impact)

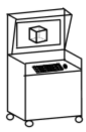
RQ2: How does MR-based BIM impact the coordination between project engineers and superintendents during MEP field issue inspection and resolution? (Organization impact)

RQ3: How does MR-based BIM impact the total duration of resolving a field-detected MEP issue? (Process impact)

3.1.1. Selection of MR technology for field testing

To increase the accessibility of 3D models in the construction field and decrease the coordination overhead, two state-of-the-practice methods and technologies for retrieving 3D models were applied in the project before this MR case study started. The first method was setting up a digital field workstation that contained a PC and display that visualize 3D models through the BIM software. The workstation had wheels to enable project engineers and superintendents to move it from one location to another in the construction field. The second method was to train project engineers and superintendents, who were previously provided with personal tablets, to visualize the 3D model using their tablets. To better understand the criteria for selecting MR for further field testing after evaluating the digital field workstation and tablets, we interviewed the VDC engineer. The interview revealed seven criteria listed in Table 2. Given the intended users' need for hands-free work and remote assistance, BIM expertise level, and ergonomics considerations, the VDC engineer decided to conduct a pilot study by using a commercially available MR hardware (HoloLens 2 Trimble XR10) and MR-based BIM software application (Spectar: https://spectar.io).

TABLE 2: Comparison of retrieving 3D model using a digital workstation, tablet, and MR headset based on the evaluation criteria.

Criteria	State of the practice:  Digital Workstation	 Tablet	Pilot study:  MR headset
1- 3D models can be used without extra preparation	✓	✓	✗
2- 3D models can be retrieved real-time	✓	✓	✗
3- Novice BIM users can operate	✗	✓	✓
4- Hands-free work is allowed	✗	✗	✓
5- Navigation in the field is easy	✗	✓	✓
6- Set-up time is less than 5 minutes	✗	✗	✓
7- Remote assist can be used	✗	✗	✓

3.1.2. 3D MR model preparation for field testing

During the case study, the VDC engineer conducted weekly meetings with the MR-based BIM software engineers to coordinate the 3D MR model preparation. From a technical perspective, the VDC engineer was able to convert a 3D model to a 3D MR model and create HoloTargets for overlaying the 3D MR model in the field by using Revit and Navisworks plug-in integrations without additional modeling needs. However, the size of the 3D model was above 1GB, which increased the model loading duration in HoloLens. In addition, the 3D MR model was displaying colored 3D geometry that indicates different designs such as structural, mechanical, architectural, etc., but the building information such as size, type, or material of the building components was not automatically transferred from the 3D model to the 3D MR model. Since efficient overlaying of the 3D MR model in the field and retrieval of useful building information were important to enhance the user experience during MR-based field inspection activities, the software engineers prepared a specifically tailored 3D MR model. They did this by sectioning it per floor and integrating the building information based on the needs of the MEP project engineers. After preparing the 3D MR models, software engineers uploaded them to the MR-based BIM software in HoloLens. The VDC engineer used these models to overlay in the construction field during MR testing with MEP project engineers and superintendents.

3.1.3. Data collection

We conducted a three-month-long case study through interviews, field observations, and project document analysis. First, we interviewed the VDC engineer and studied the BIM execution plan to model the workflow for inspecting and resolving issues with the MEP installation using Business Process Model and Notation (BPMN). We used BPMN since it is a recommended process modeling notation (buildingSMART, 2007) and applied by previous researchers (Eastman et al., 2009; Voss et al., 2013) in AECO.

The interview questions (Fig. 1) aimed to determine the boundaries of the workflow (start and end events), the project members (actors and swimlanes), activities, scenarios (gateways), and documents (data object or database) used in the current MEP issue inspection and resolution workflow (as-is) and MR-integrated workflow (to-be). These were modeled using BPMN elements to compare two workflows: one that reflected the state of the practice in the project and the second that envisions the use of MR. In addition, the durations for each activity were recorded based on the project-based observations of the VDC engineer to compare the two workflows quantitatively.

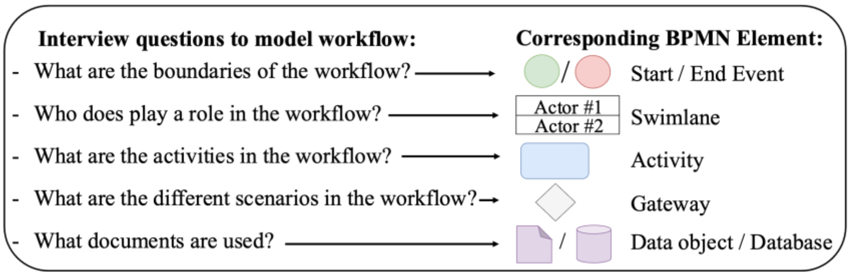


FIG. 1: Interview questions to collect workflow data and model processes with corresponding BPMN elements.

We conducted three interviews and field observations while four MEP project engineers and two superintendents were using MR to simulate their inspection tasks in the construction field. During each field test, the VDC engineer wore the HoloLens and overlaid the 3D model using the MR-based BIM software. The HoloLens display was cast to a smart tablet using the Remote Assist feature (Fig. 2). Interviewees requested the MEP components that they wanted to inspect in real time. The VDC engineer clicked on the virtual MEP object through HoloLens, and a popup window showing the related building information was opened. The interviewees read the building information list on the tablet and compared it to their physical inspection. MEP engineers and superintendents were asked the following questions to determine the usefulness of the building information visualized through MR:

1) Do you need this information during the field inspection?
2) If yes, how do you use this information during the inspection?
3) What other information do you need to complete your field inspection?

The interviews were video recorded through HoloLens to capture the building information evaluated during the field tests. Additional audio recordings, photos taken during the interviews, and field notes supported the data collected through the HoloLens video recordings.

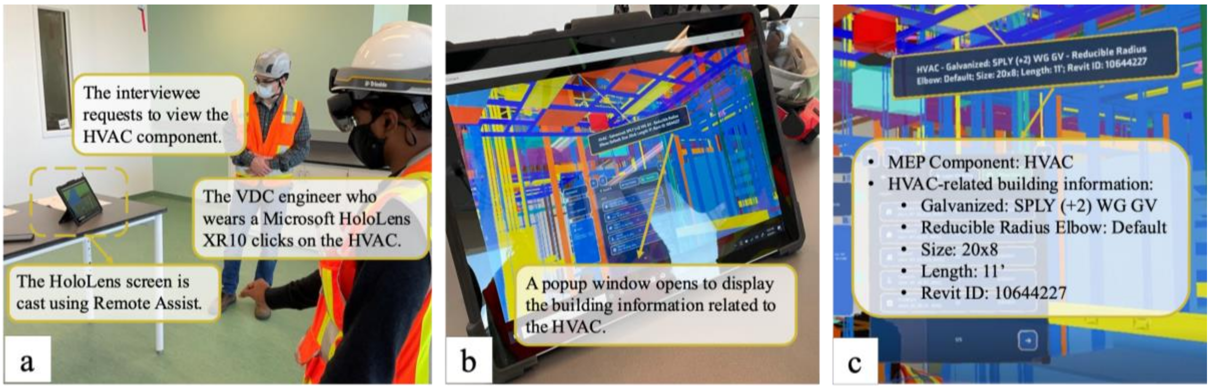


FIG. 2: The interview setting during MR-based field inspections: (a) the interviewee requests to view a building component, (b) a popup window opens in the MR interface, and (c) displays the related building information.

3.1.4. Data analysis

The case study data were analyzed using both qualitative and quantitative techniques to provide an in-depth understanding of the role of MR technology in enhancing construction project processes. Using BPMN principles, we modeled the current issue resolution workflow (as-is) and the MR-integrated issue resolution workflow (to-be). We compared as-is and to-be workflows (Fig. 3) in terms of the change in the number of hours spent for coordination between project engineers and superintendents to resolve an MEP field issue to quantify the expected coordination overhead impact on the organization. For the process impact, we estimated the total duration for resolving a field issue in each workflow and identified the change in terms of the number of hours.

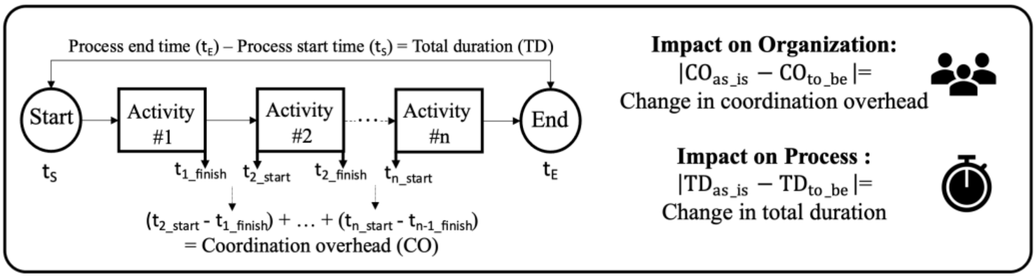
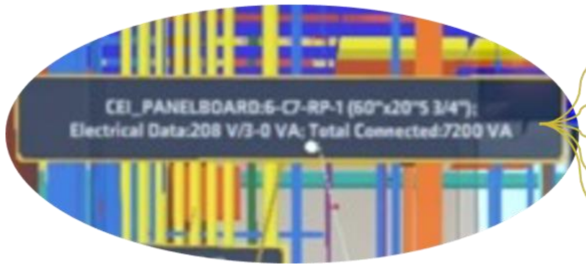


FIG. 3: Analyzing organizational and process impacts in terms of the change in coordination overhead and total duration.

We analyzed the content of field observations and interviews through qualitative coding. Using line-by-line coding in Nvivo 12, we divided the interviews into utterances and labeled each utterance based on the MEP building component that the interviewees referred to. This helped us to determine which MEP components receive higher attention from MEP engineers and superintendents, and consequently, the product impact of MR-based inspection on specific MEP components.

To assess the relevance of building information for MR-based field inspection tasks, we developed a usefulness classification of building information (Fig. 4). The classification system includes four categories. Useful information shown in **green** represents relevant and actionable information to complete a task. Neutral information shown in **yellow** is contextual information that is not necessarily actionable. Not useful information shown in **gray** is information that is irrelevant to complete the task. Missing information shown in **red** is the information required for task completion but not embedded in the 3D MR model. By applying this classification, we analyzed the usefulness of MEP building information visualized in MR.



Building Information	Purpose	Classified Usefulness
Panelboard	To confirm the device type	Useful
6-C7-RP-1 (60"x20"5 3/4")	To determine installation locations – not critical during inspection.	Neutral
Electrical Data: 208 V/3-0 VA	N/A	Not useful
Total Connected: 7200 VA	N/A	Not useful
Additional information need Power type: Normal	To differentiate normal, standby, and emergency power types	Missing

FIG. 4: Classifying the usefulness of building information visualized in MR based on its purpose during the inspection.

4. FINDINGS

The following two subsections present our case study findings. Based on the findings from qualitative coding on video-recorded mechanical, electrical, and plumbing field tests, Section 4.1. presents the product impact of MR-based inspections (RQ1) on MEP components and classifies the usefulness of MEP building information to facilitate MR-based inspection activities. Section 4.2. presents the findings based on as-is (non-MR) and to-be (MR-integrated) MEP field issue resolution workflow comparison. Based on the workflow comparison, it demonstrates the estimated impacts on the organization (RQ2) and process (RQ3) in terms of the change in coordination overhead between superintendents and project engineers to resolve an MEP field issue and the total duration of field issue resolution.

4.1.Findings of MR-based MEP field inspection tests

4.1.1. Product impact

From the product perspective, timely identification and resolution of field issues impact the quality of construction work in the field. Focusing on the MEP components, this study demonstrates that MR-based field inspection can increase the installation quality of MEP components by helping project engineers identify field issues that would be difficult to detect otherwise. The 3D MR model overlaid in the field consisted of 3D geometry that is colored differently for mechanical, electrical, and plumbing components and their related building information. During interviews, project engineers and superintendents agreed on the usefulness of overlaying 3D geometry in the field. They indicated that comparing the 3D model with the work-in-progress fieldwork would help them catch misalignments easily and determine potential solutions.

MEP project engineers and superintendents requested to review 9 MEP components using MR during three field tests focusing on the electrical, mechanical, and plumbing components respectively. During the mechanical one, engineers and superintendents mainly reviewed heating, ventilation, and air conditioning (HVAC) components over the ceiling: HVAC variable air volume (VAV), HVAC grills, HVAC diffuser, and HVAC air handling unit (AHU). In the electrical tests, electrical receptacles and panelboards were inspected through MR. Lastly, in the plumbing tests, water supply pipes and lab vent pipes were reviewed. Line-by-line qualitatively coded transcripts of field tests determined the number of times each building component was mentioned by the engineers and superintendents during MR-based inspection tests in the field. Among the 9 MEP components, HVAC ductwork, and water supply pipe received the highest emphasis from MEP engineers and superintendents compared to other components.

In addition to highlighting specific MEP components, field tests provided insights into the specific inspection tasks that MR can assist with. MEP engineers and superintendents shared several use case examples with the specific activities that they would use MR for field inspection. For mechanical components, reported inspection activities focused on checking the material of HVAC ductwork, reading the cubic feet per minute (CFM) value during balancing of HVAC, and checking the accessibility of HVAC grills considering the operability requirements. For electrical components, the use cases focused on checking for physical clashes, power types, and the number of circuits. For plumbing inspections, the engineers and superintendents indicated that they would compare the installation of lab vent pipes to the 3D model using MR to evaluate the accuracy and progress of installation during in-wall inspections. These use cases suggest that MR can support various MEP field inspection activities at different phases of construction, helping project engineers and superintendents accurately inspect the MEP components, identify issues earlier, and potentially increase the MEP installation quality.

An example that illustrates the impact of MR-based inspection on HVAC Ductwork material inspection: "*if you're doing this job walk inspection and you have flame bar ductwork in this project which is fire-rated ductwork. If the model shows it is a flame bar and it is not…I mean it takes 8 weeks to get out here. So, it is definitely something you want to catch.*". This example provided by one of the MEP engineers suggests that early identification of incorrect ductwork material would increase the accuracy of MEP installation and eliminate the potential schedule impact of 8 weeks.

4.1.2. MEP building information retrieval during construction field inspections

During field inspection, MEP engineers and superintendents need to retrieve information that is relevant and timely to complete the inspection efficiently and accurately. We applied the usefulness classification as a criterion to determine the relevance and timeliness of information to resolve potential issues. Case study-specific findings showed that 32% of reviewed data points were useful, 7% neutral, 16% not useful, and 45% missing (Fig. 5a). Fig. 5b shows the classification of reviewed 48 data points in this case study based on whether the data point was initially requested, whether the data point is available in the 3D model, and whether the data point is integrated to provide a more detailed analysis for the building information usefulness. 17 data points were excluded from the analysis since they were initially requested but not revisited during interviews. Table 3 shows the case study-specific usefulness classification of 31 building information data points after excluding 17 data points.

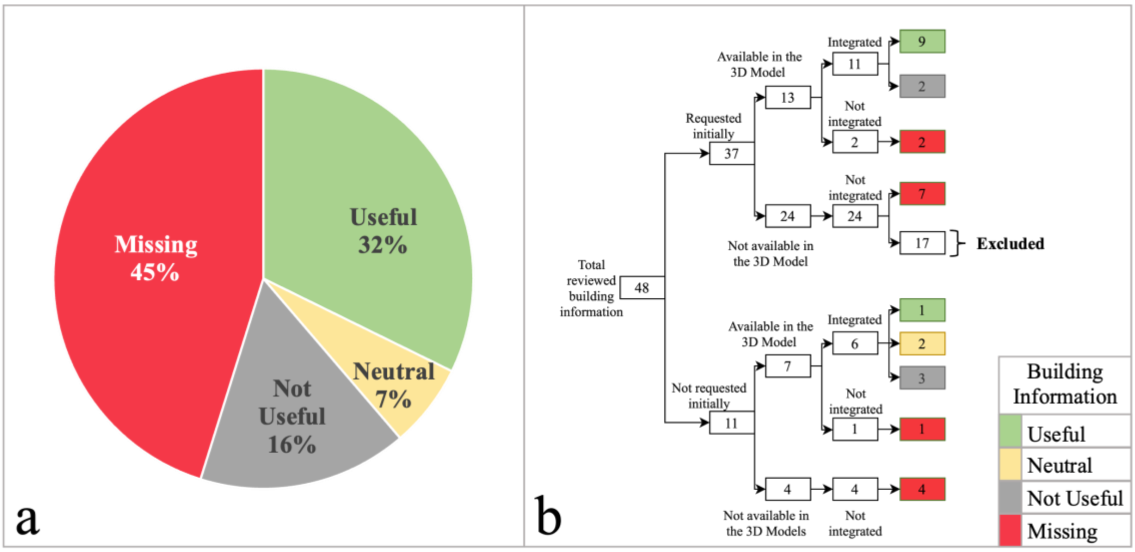


FIG. 5: *Applying the proposed classification of building information usefulness to the case study: (a) distribution of building information usefulness (b) detailed analysis of classified information.*

From 37 data points that the MEP engineers initially requested from the software company to integrate into the 3D MR model, only 13 (35%) were available in the 3D source models (in NWD and RVT formats). The remaining 24 data points were available in 2D drawings or submittals that are used during MEP installation or inspection, but not linked to the 3D source models. Therefore, software engineers could not integrate them into the 3D MR model automatically. Out of 13 data points available in the 3D source models, 11 data points were integrated by the software engineers. Most of the requested and available information (9 out of 13) was confirmed as useful by the MEP engineers and superintendents in the field. However, 9 data points that were requested but not integrated were detected during the field tests and classified as missing. Out of 9 data points, 7 of them were also missing in the 3D source files that were used to prepare the 3D MR model.

Additionally, the software engineers integrated 6 data points that were available in the 3D models, but not initially requested by the MEP engineers. One of them, "length", was found useful for the inspection activities. Two of them, "color of the system" and "offset", were found neither useful nor not useful; hence, we classified them under neutral information. The other 3 data points were classified as not useful for the inspection tasks based on the field interviews. Regarding the building information classified as not useful, MEP engineers and superintendents mentioned that these data points can be useful for installation or commissioning activities, but not for inspecting the installation quality and progress. Also, overlapping information such as “device identifier” and “electrical fixture type” made the latter redundant for field inspection.

TABLE 3: Case study-specific usefulness classification of 31 building information data points reviewed in MR.

ID	Useful	ID	Missing
1	Cable type (CAT-6, CAT-5a, copper, etc.)	18	Associate bulletin package
2	Conduit size	19	Associated exhaust fan/AHU
3	Device identifier (lighting control, lighting switch, etc.)	20	Associated spool number
4	Duct size	21	CFM value of grills
5	Length	22	Circuit numbers in conduit
6	Material type (stainless, galvanized, etc.)	23	FSD associated system tag
7	Pipe size	24	Height of pipes
8	Pressure gauge	25	Panel count
9	System description1 (chilled/hot water or return/supply/exhaust)	26	Power type (normal, standby, emergency, etc.)
10	System description2 (N_2, compressed air, reverse osmosis, etc.)	27	Receptacle associate circuit
	Neutral	28	The location of the diffusers on floor plan
11	Color of the system (e.g., hot water - red)	29	VAV box
12	Offset	30	VAV tags
	Not Useful	31	X-Y coordinates of the device from the center
13	Electrical fixture type		
14	Number identifier		
15	Pipe type		
16	Revit ID		
17	Voltage		

Conducting field observations and interviews while MEP engineers and superintendents evaluated the building information integrated into MR provided insights for more effective utilization of MR. First, necessary building information for field inspection tasks needs to be integrated into the 3D model early in the construction project, ideally in the preconstruction phase before the 3D model is signed off and construction submittals are finalized. As previously noted, it was not feasible for software engineers to manually review the building information in the 2D drawings to integrate them into the 3D MR model. Therefore, they integrated the building information that was already available in the 3D source models. Second, the identification of necessary building information is an iterative process, which requires successive refinement for continuous improvement. For example, MEP engineers provided a list of building information they needed before the field tests. During the field tests, they reported that 2 data points that they initially requested were not useful, and they would need 5 additional data points for their inspection tasks, which they initially did not request. This can be partly attributed to the advantage of MR-based information visualization. Simulations of information retrieval through MR during field tests helped MEP engineers to reevaluate their task-specific information needs. Another aspect that partly helped MEP engineers reconsider the building information needs was the participation of MEP superintendents in the field tests. Although initial requests for building information were made by the MEP engineers, MEP superintendents provided an additional perspective based on their internal quality inspection tasks following the installation of MEP components.

4.2. As-is and to-be field issue resolution workflows

Analysis of the workflow data collected during the interviews with the VDC engineer showed that there could be three workflow scenarios to resolve MEP field issues between the general contractor and the engineering design company:

- **Scenario 1:** When the issue does not violate the design intent, the general contractor can resolve the MEP issue without filing an RFI. The only meeting in the workflow is between superintendents and project engineers to review the issue.

- **Scenario 2:** When the issue violates the design intent, the general contractor needs to file an RFI to resolve the MEP issue. In addition to the issue review meeting, project engineers need to schedule a meeting with designers to discuss the RFI.
- **Scenario 3:** When the general contractor needs to file an RFI to resolve the MEP issue and the designers need to understand field conditions before approving the RFI, a field visit is scheduled. In addition to the issue review meeting and the meeting to discuss the RFI, project engineers need to coordinate the designer's field visit to review the issue in the field.

Fig. 6 presents each scenario to resolve MEP field issues between the general contractor and the engineering design company based on two gateways: (G1) RFI is needed to resolve the field issue and (G2) designers need to visit the field to approve the RFI. The project requirements reflected in each gateway increase the workflow complexity by adding additional tasks, meetings, and required documentation.

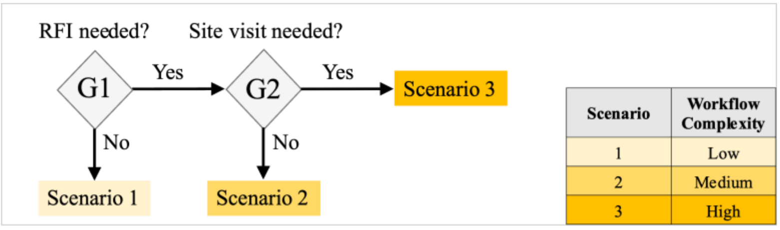


FIG. 6: Scenarios of MEP field issue inspection resolution workflow with increasing complexity.

The three scenarios were used to formalize respective as-is and to-be workflows using BPMN elements namely start and end events, activities, gateways, data objects, and databases (Fig. 7). While the as-is workflow (Fig. 7a) shows the conventional method that the project team follows between identification and resolution of an MEP field issue, the to-be workflow (Fig. 7b) reflects the integration of MR during field inspection and virtual site visits. Both workflows include the same 4 swimlanes to indicate activities, events, gateways, and data objects specific to project members, e.g., superintendent, project engineer, cost control engineer, and designer. Since the VDC engineer's role is to support project engineers, we did not model a separate swimlane for their activities.

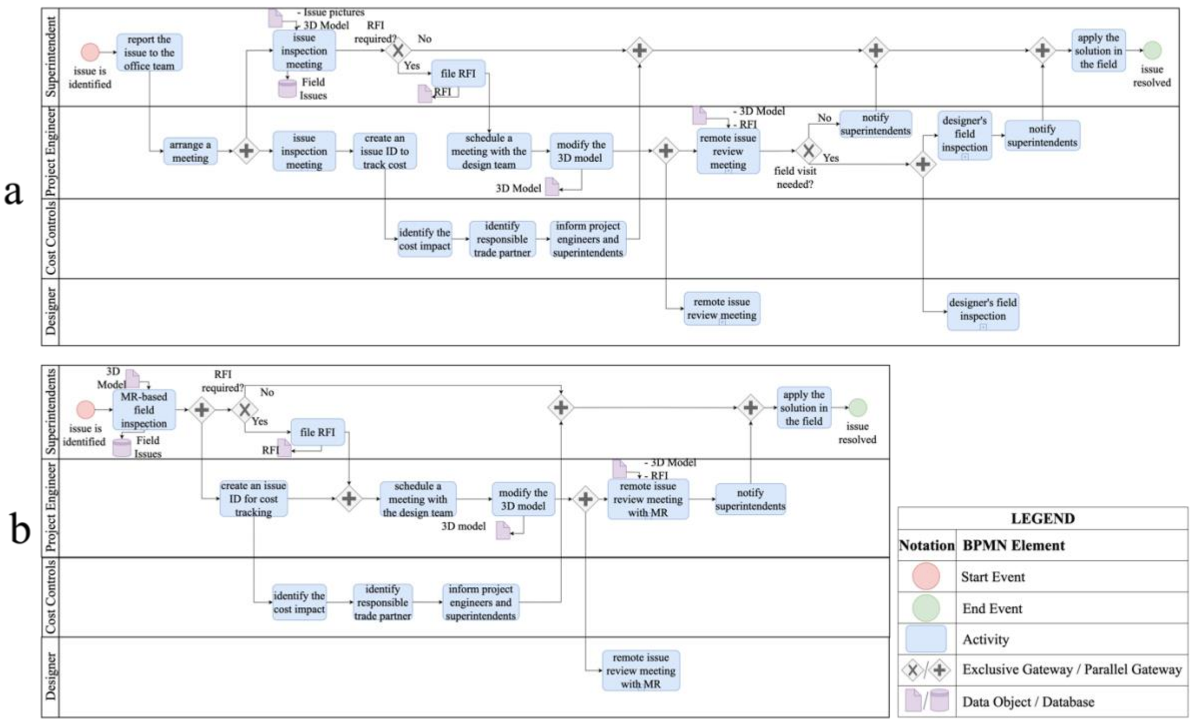


FIG. 7: MEP field issue resolution workflows modeled using BPMN elements: (a) state-of-the-practice (as-is) workflow (b) MR-integrated (to-be) workflow.

4.2.1. Organizational impact

The integration of MR technology into the issue resolution workflow impacts how different organizational units collaborate, and consequently, how project team roles and responsibilities change. In the to-be workflow, the first MR use case is designed for superintendents to inspect the issue by overlaying the 3D model, retrieve related building information, decide on a solution, and report the issue to the project engineers with the proposed solution. It eliminates the need for a meeting between superintendents and project engineers to review the issue in Scenarios 1, 2, and 3. The second MR use case is a virtual field visit for Scenario 3. Designers can virtually inspect the issue when the project team can call designers via Teams in HoloLens using the Remote Assist feature and share their MR-based BIM software screen that shows the 3D model overlaid in the field. It eliminates the need for designers to travel to the field for inspection and increases the efficiency of issue resolution.

By decreasing the coordination effort to schedule additional meetings and potential project delays, MR-based inspections reduce the coordination overhead between superintendents and project engineers to resolve an MEP field issue. Analytical workflow comparison revealed that the coordination overhead can be decreased by approximately 75% (28 hours to 6 hours) in Scenario 1, by 50% (47 hours to 23 hours) in Scenario 2, and 65% (72 hours to 24 hours) in Scenario 3 (Fig. 8). In addition, MR-integrated to-be workflow can empower superintendents to inspect the field issue without requiring assistance from project engineers.

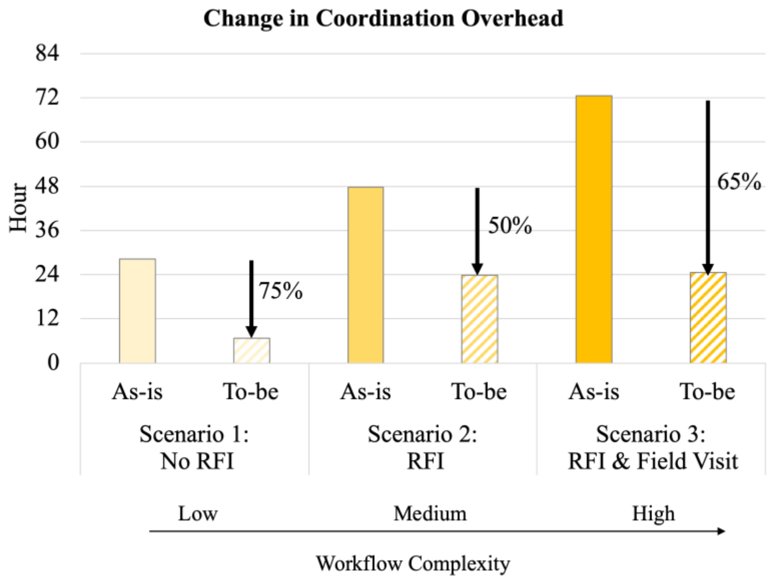


FIG. 8: Example of how MR-based field inspections can decrease the coordination overhead during MEP field issue resolution.

4.2.2. Process impact

Understanding the potential process impact of MR-based field inspections guides project teams to decide whether to integrate MR into their current work processes. It also helps project schedulers consider the expected impact while planning inspection activities. In this case study, we used the total duration of resolving an MEP field issue as a key performance indicator of the issue resolution process. The total duration that is estimated through workflow analysis reflects the shortest issue resolution duration as opposed to the average total duration. This is important to highlight because if the MEP issue detected in the field is on the critical path, it is prioritized and resolved as soon as possible. When it is not on the critical path, it is not a priority for the MEP engineers and may be resolved much later.

Similar to the impact on the organization, our workflow analysis shows that the complexity of the issue resolution scenarios impacts the shortest total duration to resolve an MEP issue. In this case study, the state of the practice shows the shortest duration to resolve a field issue is 2 days in Scenarios 1 and 2, and 3 days in Scenario 3 (Fig. 9). The to-be MR-based field inspections decrease the total duration to resolve an MEP issue by 1 day in Scenarios 1 and 2, and 2 days in Scenario 3 based on the workflow comparison.

Workflow Complexity

Low → Medium → High

	Scenario 1: No RFI		Scenario 2: RFI		Scenario 3: RFI & Field Visit	
	As-is	To-be	As-is	To-be	As-is	To-be
Total duration	2 days	1 day	2 days	1 day	3 days	1 day

FIG. 9: Example of how MR-based field inspections can decrease the total duration of resolving an MEP field issue in this case study.

Using the workflow data provided by the VDC engineer, we assumed that meetings between project engineers, superintendents, and designers can be scheduled for the following business day, resulting in the shortest workflow duration. However, the unpredictability of scheduled meeting times or the time that designers can travel to the field may result in potential delays. For example, a field issue can be hypothetically resolved in Scenario 2 and Scenario 1 in the same number of days; however, any delays in the RFI discussion meeting with designers would directly result in a longer issue resolution duration in Scenario 2. As MR-based field inspections decrease the need for scheduling additional meetings in the to-be workflow, it may be possible to resolve an MEP field issue by the end of the next day after the issue is identified. The opportunity of decreasing the total duration to resolve an MEP field issue regardless of workflow complexity helps project teams avoid schedule overruns.

5. CONCLUSION

This paper presents a case study on MR-based construction field inspection and estimates the potential project-based impact by focusing on the resolution of identified MEP issues. Our research extends the previous studies on MR-based field inspection by quantifying the organizational and process impact through workflow comparison, assessing the product impact through field observations of MR-based MEP field inspection tests, and providing a classification for determining useful building information to integrate into the 3D MR model.

From a product point of view, preliminary findings from the field interviews show that MR-based inspection can increase the quality of MEP installation by making errors easier to detect and enabling faster resolution. We observed that effective utilization of MR during field inspection requires retrieval of relevant and timely building information. Hence, project teams need to integrate all necessary building information for the construction inspection activities to 3D models during the BIM coordination stage of construction projects. Based on our classification, we recommend that missing data points be included, and useful and neutral data points be kept. Since displaying unnecessary information about the task at hand increases the workload of users (Zhu et al., 2010), the data points that were identified as not useful based on our building information usefulness classification should be removed from the 3D MR model by VDC engineers in the project or MR-based BIM software engineers. This is a feedback loop upstream to MR-based BIM software developers that take a user-centric approach as a function of the task at hand. In addition, dynamic real-time functionalities of MR-based BIM software allowing users to add or eliminate, hide, or show specific data needs depending on the project phase, user, and task will be desirable in future MR applications.

The as-is and to-be workflow comparison using BPMN indicates that MR use for inspection and virtual site visit purposes can (1) decrease coordination overhead between superintendents and project engineers by up to 75% from an organizational point of view, and (2) reduce the shortest total duration of resolving a field issue at least by 50% from a process point of view. When a field visit is necessary to resolve the issue, the project team can resolve field issues faster with less coordination overhead through MR-based self-inspection and virtual field visits. By decreasing the need for meetings, MR reduces the uncertainty of issue resolution duration due to potential delays in scheduled meeting times. Our project-specific findings provide insights for construction project managers or VDC managers to decide whether to deploy MR for construction inspection at similar-type projects and to track the project-specific goals of MR deployment. Managers can replicate the workflow analysis and use the field interview questions to further examine the use of MR during inspection activities in construction projects. For example, if designers are collocated on the project site, MR-based virtual field visits may improve the coordination overhead less than in the case of geographically dispersed designers. Moreover, when MR-based inspections are implemented during or right after MEP installation, they can proactively prevent the rework activities for field-detected issues, improve installation quality, and decrease the coordination overhead between the field and the office.

This 3-month-long case study was limited by the fact that the construction project was in the commissioning phase, which precluded us to observe the MEP installation and inspection phases in real time. Hence, our as-is and to-be workflow comparison was based on the workflow information collected throughout the meetings with the VDC engineer whose role was to coordinate MEP field issues. Consequently, our findings reflect the analytical impact on coordination overhead and shortest total issue resolution duration, as opposed to the empirical impact. Likewise, the impact on installation quality was based on our qualitative interviews with the superintendents and project engineers. Further research needs to observe the impact of MR-based field inspection over the construction phase in real time and validate the building information usefulness classification through multiple case studies.

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